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13. ABSTRACT (Maximum 200 words)

A program for feature detection and estimation using nonlinear and multiscale analysis was completed. The state-of-the-art edge detection was combined with multiscale restoration (as suggested by the first author) and robust results in the presence of noise were obtained. Successful applications to numerous images of interest to DOD were made. Also, a new market in the criminal justice field was developed, based in part, on this work.

14. SUBJECT TERMS
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24

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20. LIMITATION OF ABSTRACT

A program for accurate feature detection and estimation using nonlinear analysis was completed. The basic edge/feature detector was originally devised by Dr. Rudin in his thesis [1]. Improvements using multiscale analysis for the basic edge detection task were instituted during the life of this contract. A very important breakthrough came when feature detection was combined first with Cognitech's total variation based restoration of noisy blurred images as described in [2,3,4] and second with a state-of-the-art segmentation device originating in the work of our consultant, Professor J.-M. Morel and improved significantly at Cognitech by Rudin and Nordby, in collaboration with our French consultants [5,6].

The capabilities of our total image processing/feature detection approach can be best displayed by the results on various images. Figure 1a shows an original 512 × 512, 256 grey level "airport image". Figures (1a,b) show conventional edge detectors applied to this image. Rudin's multiresolution edge detector uses rotated masks as shown in figure 2a, while figures 2(b-d) demonstrate the improved edge detection performance of this method as compared with Figures 1(b,c). The localized masks pick up more edges, and thus retains a pleasing sharpness to the features. Figures 3 and 4 demonstrate a similar comparison on the "pentagon" image.

Of course, the robust performance of a feature detector in the presence of noise is crucial to its utility. Figure 5a shows the "airport" image plus additive noise of standard deviation 15. Figure 5b shows conventional edge detection applied to that noisy image. Figures (5c,d) show Rudin's multiscale edge detector with two different mask signs applied to that noisy image. Features were captured with very little spurious information retained.

In figure (6a) we show the result of Cognitech's total variation (TV) based restoration combined with segmentation, as suggested by Rudin, applied to figure (5a). Figure (6b) displays the results using a Wiener filter – other conventional approaches fare as badly. Figure (6c) shows Rudin's edge detection applied to the TV restored image. It is interesting to note that this result is comparable to a conventional edge detector applied to the *original* (nonnoisy, image (1a,c)). Figure (6d) shows edge detection of the Wiener restoration

Figure (7a) shows a very noisy version of Figure (3a). Conventional edge detectors give poor results – see (7b). However, Rudin's multiscale edge detection performs acceptably – Figures (7c,d).

The key results came first through TV restoration, without using segmentation as seen in Figure (8a) and the state-of-the-art edge detection in Figure (8b). These results compare to those in Figure (3c) on the clean image, using a conventional method.

Next, Figure (9a) shows the results of TV restoration with segmentation and Figure (9c) shows the resulting edge detection. These seem to give even better results than those displayed in Figure (3c) on the clean image. Figure (9b) displays the poor results of a Wiener filter restoration and Figure (9d) shows edge detection of that.

Figure (10a) shows an original picture of a chemical plant and Figure (10b) shows the edge map of (10a) using Rudin's edge detector. Figure (10c) shows *multiplicative* noise of standard deviation 0.3 applied to this image and (10d) displays the edge map. In (10e) and (10f) we first restored the images using conventional (least-squares and Wiener filter) restoration techniques, while in Figure 10g) we display Cognitech's state-of-the-art TV restoration with segmentation, followed by Rudin's edge detector. Contrast (10g) with (10e,f) and compare it to (10b). The results are striking.

Figure (11a,b) show before: the "jelly-bean" image, then after: it is corrupted by a sizable amount of multiplicative noise. Figure (11c) shows the restoration using Cognitech's TV filters and (11d) shows the remarkable results possible using segmentation of the original, clean image – highlights and edges are obtain clearly. Of course, this ideal segmentation is usually not possible.

In Figure (12b,c) we show the results of conventional restoration while in (13,t1-3) we show the results of iterating segmentation and denoising in Figure (13b), with intermediate steps shown in Figures (13c,d). As the iteration proceeds, the restoration approaches the ideal case of Figure (11d).

Figures (14a,b) show the before and after version of the clean and noisy (via multiplicative noise) of the "chemical plant" image. Figure (14c) shows the TV based denoising and Figure (14d) demonstrates this using the ideal segmentation. Figures (14e,g,h) show various conventional restorations of Figure (14b), while (14f) provides the segmentation of the Wiener-filter restored map at a chosen scale. Figure (15c) shows the restoration of this image using Cognitech's TV filter while Figure (15d) shows the extremely impressive restoration using TV filter with segmentation. Incredibly, the texture of the field in the upper right corner of (15a) is denoised and restored. We are currently investigating this phenomenon.

Cognitech achieved great success in transferring this technology to a new market, it has helped to develop – namely the field of criminal justice. As described in SIAM News, December 1993 issue [7] and in many local and national news stories our restoration algorithm was used to help identify a defendant in the Reginald Denny/LA Riots trial. Figure (16a) shows the original image taken by a news reporter from a helicopter. To help identify the rock-throwing suspect we concentrated on $\frac{1}{6000}$ of the image on his arm. Figure (16b) shows an expansion of this region using Cognitech's anisotropic diffusion expansion algorithm. Figure (16c) shows segmentation of the arm (admitted into court proceedings for the first time ever) showing the suspected tattoo. Figure (16d) shows the segmentation/reconstruction of the arm and Figure (16e) shows a comparison of the reconstructed image and actual tattoo. Identification of the suspect was made by the jury.

Cognitech then moved into this area and performed numerous image/video processing tasks for criminal justice applications. Figure (17a,b) shows two stills from a video of a jewelry store robbery. In Figure (17c) we just interlaced the two fields, but in Figure

(17d) we matched frames using our new frame fusion algorithm. Figure (17e,f) show the improvements in detail via our frame fusion algorithm. Finally in Figure (17g), we restored (17f) using our TV filters. This evidence was crucial in the outcome of that case – see [8].

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[1] L. Rudin, "Images, Numerical Analysis of Singularities, and Shock Filters", Cal-tech Comp. Sc. Dept. Report # TR:5250:87 (1987).

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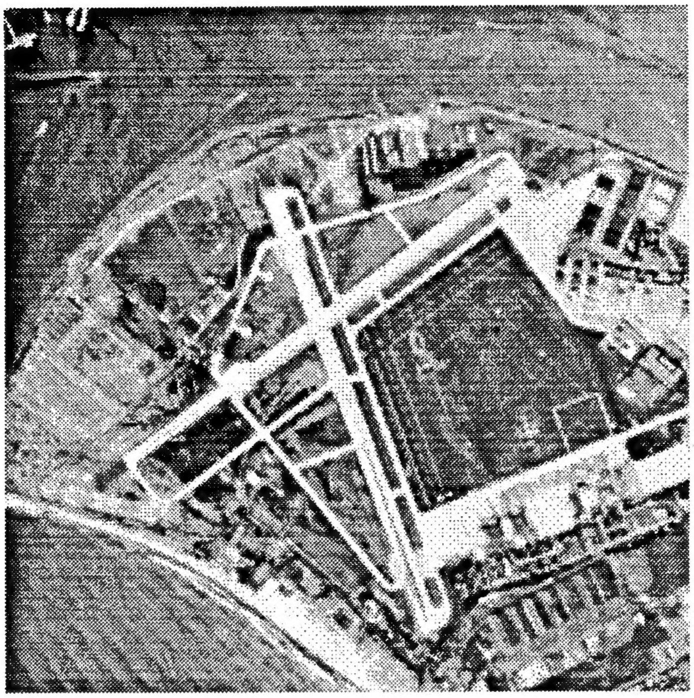
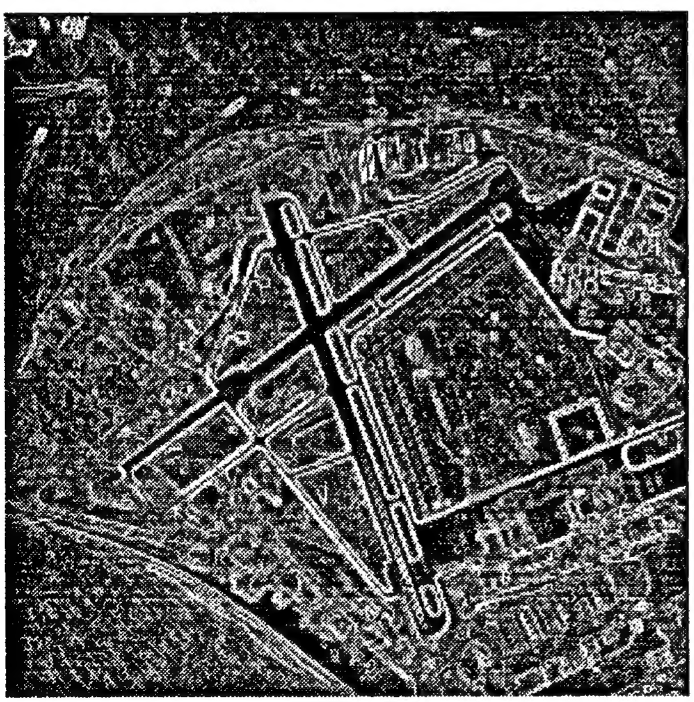
[6] L. Rudin, G. Koepfler, F. Nordby, and J.-M. Morel, "Fast Variational Algorithm for Clutter Removal Through Pyramidal Domain Decomposition", SPIE, San Diego, CA (July, 1993).

[7] "Image Processing Makes its Mark in Court", SIAM News, Vol. 26, #81 (Dec. 1993).

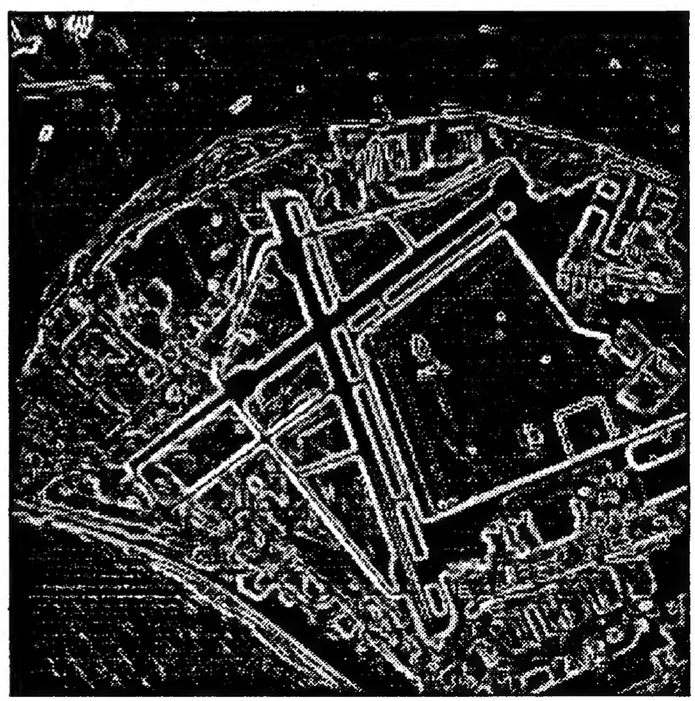
[8] "Cognitech Thinks it's Got to a Better Forensic Tool", Los Angeles Times, Business Section, (September 5, 1994).



a) Original "Airport"

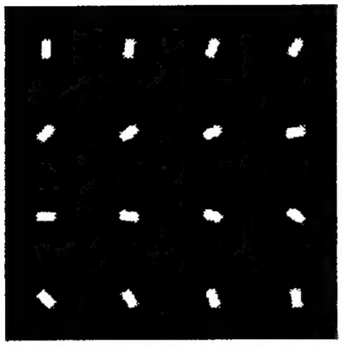


b) Roberts edge detector

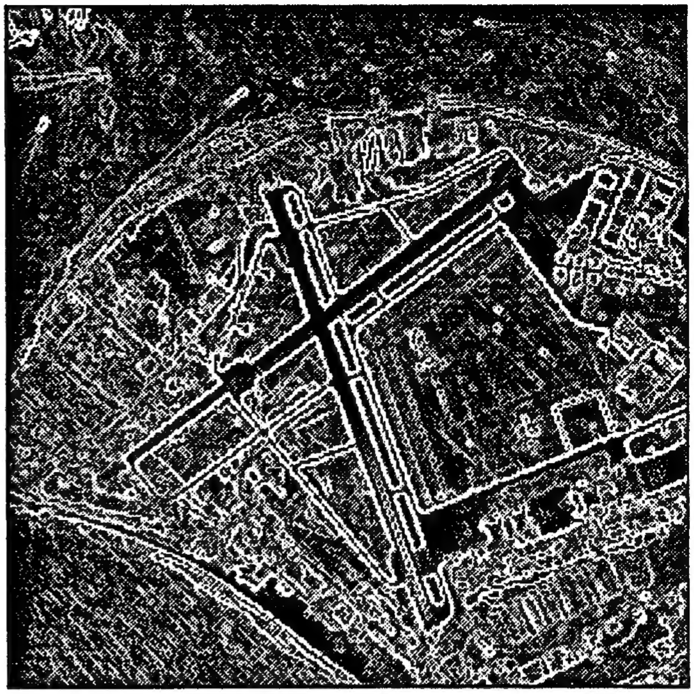


c) Sobel edge detector

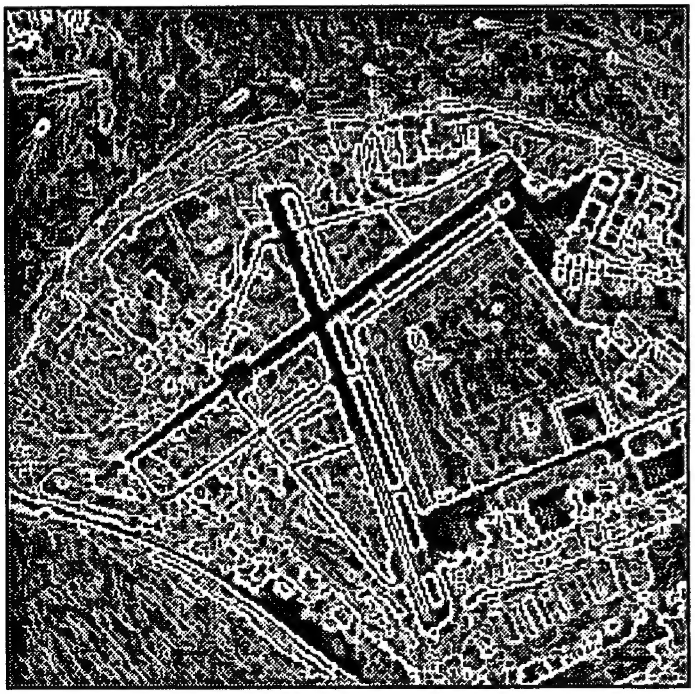
Figure 1



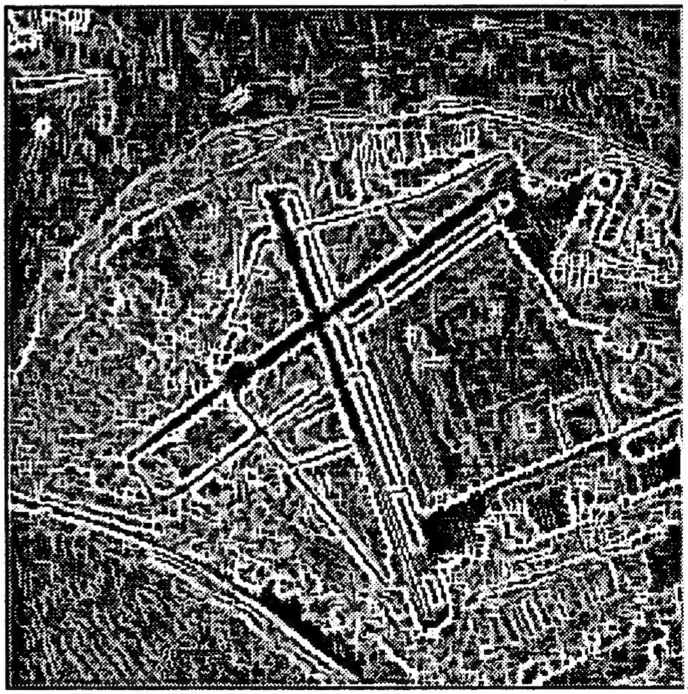
a) Rotated masks 2x3



b) Rudin edge detector with mask 1x1

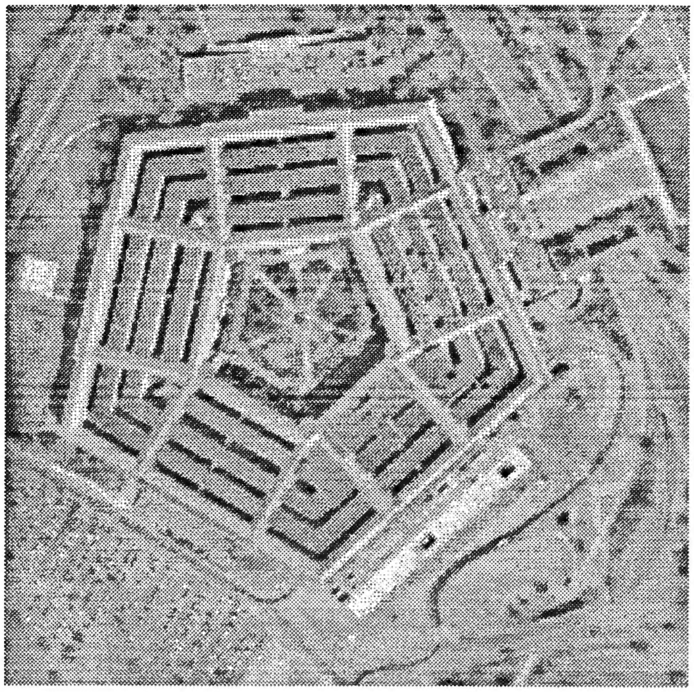


c) Rudin edge detector with mask 1x2

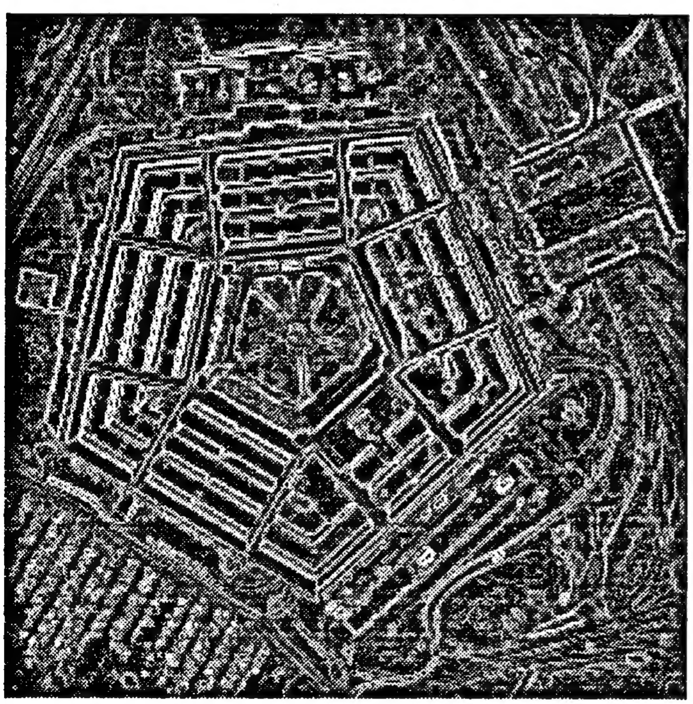


d) Rudin edge detector with mask 1x4

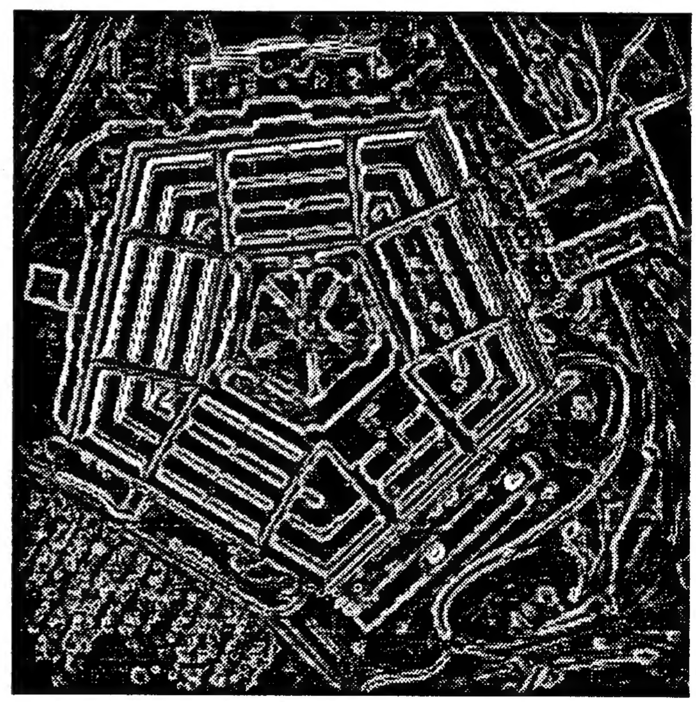
Figure 2



a) Original "Pentagon"

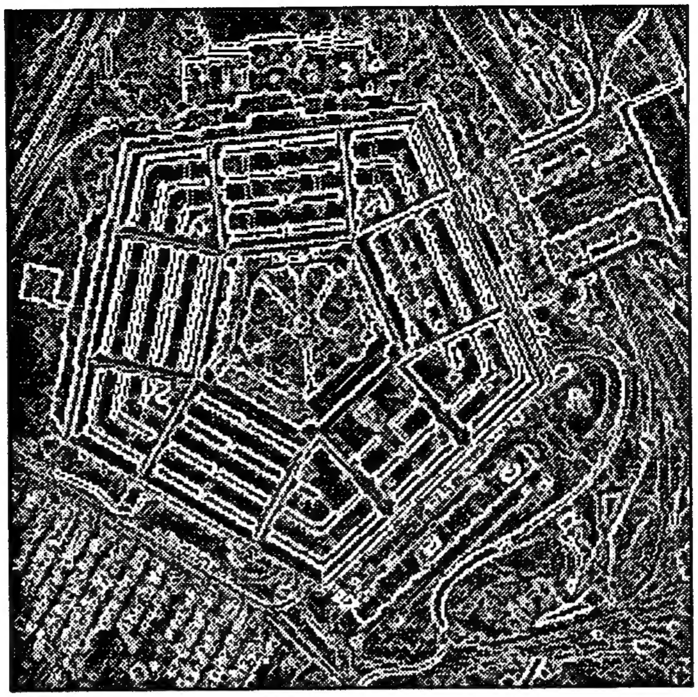


b) Roberts edge detector

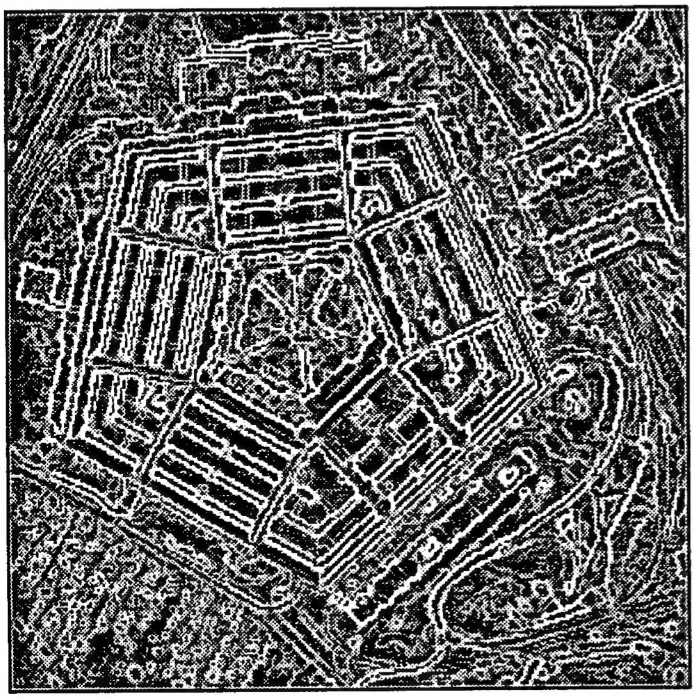


c) Sobel edge detector

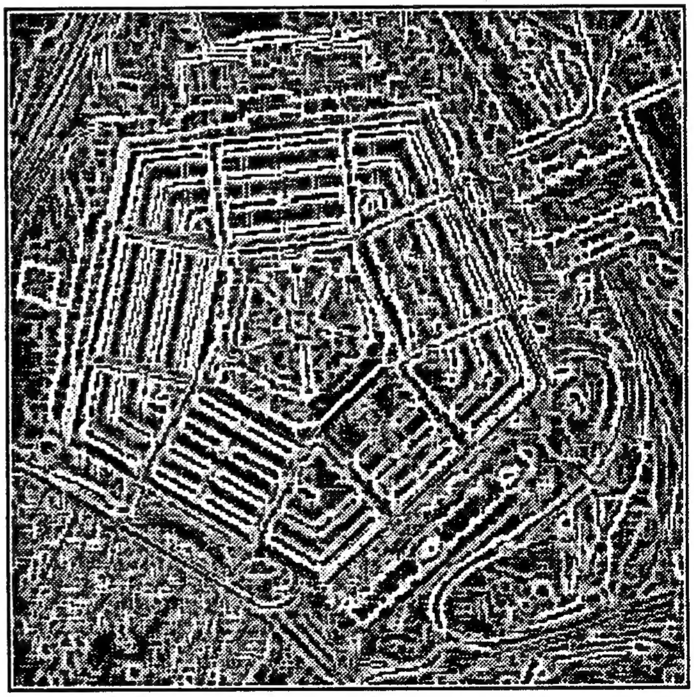
Figure 3



a) Rudin edge detector with 1x1 mask

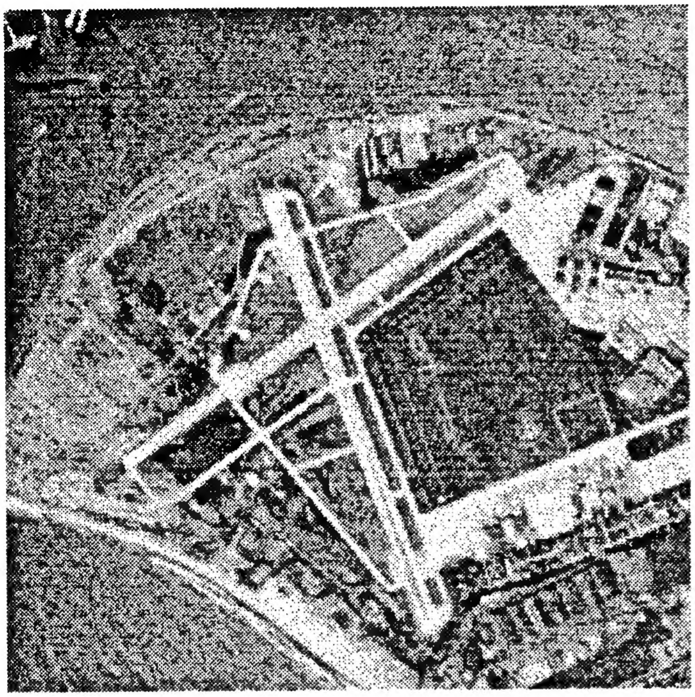


b) Rudin edge detector with 1x2 mask

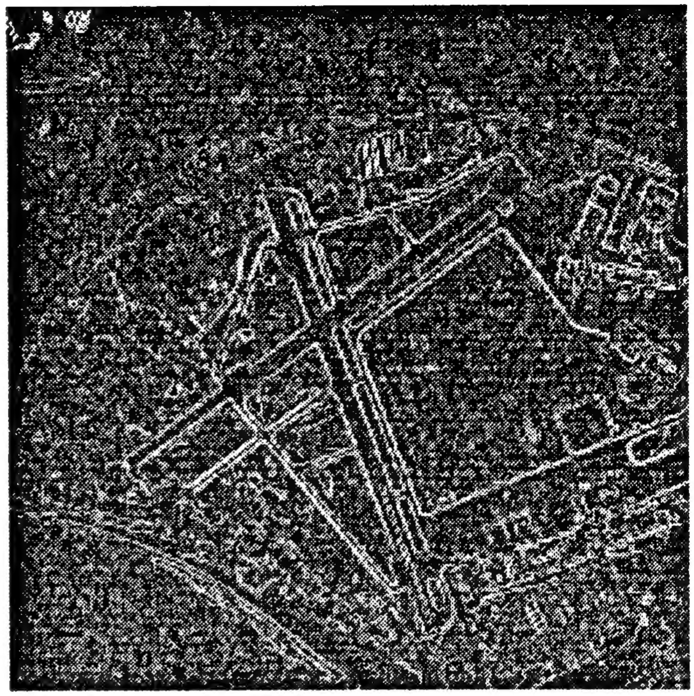


c) Rudin edge detector with 1x4 mask

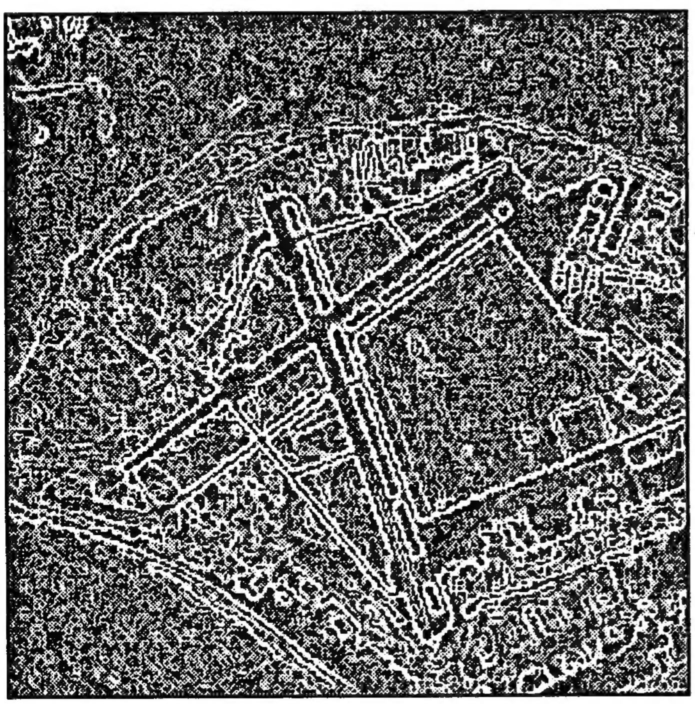
Figure 4



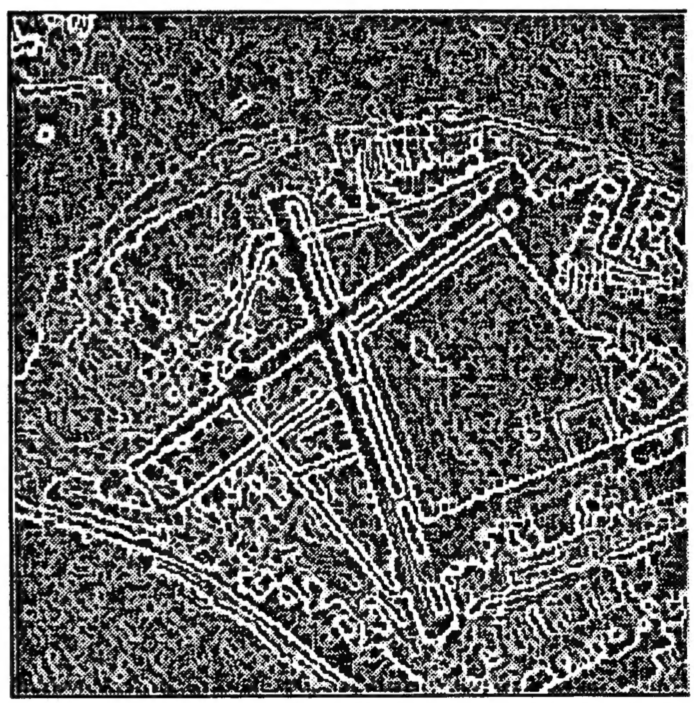
a)"Airport" plus additive noise
with st.dev. 15



b) Roberts edge detector

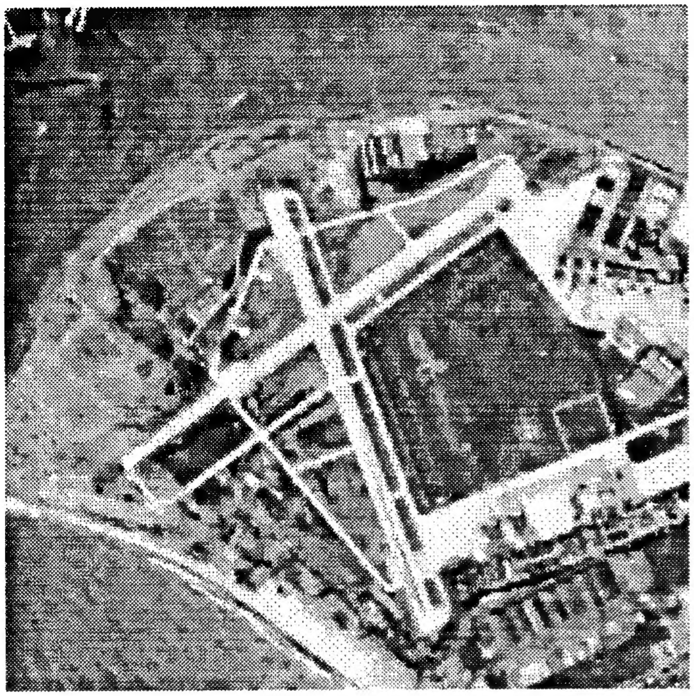


c) Rudin edge detector with 1x2 mask

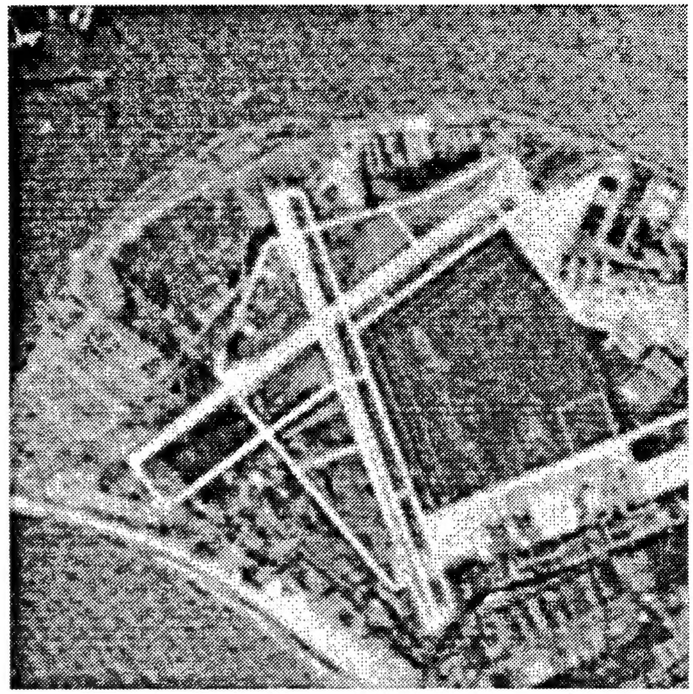


d) Rudin edge detector with 2x3 mask

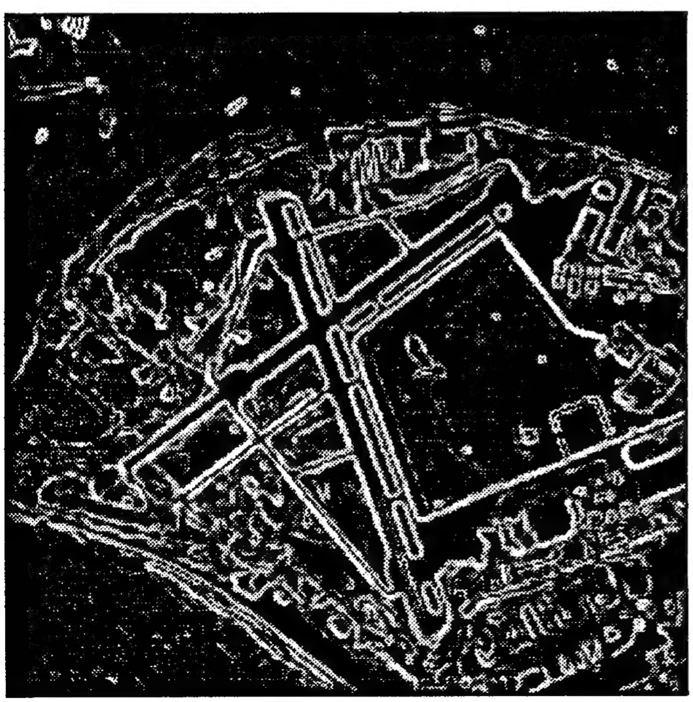
Figure 5



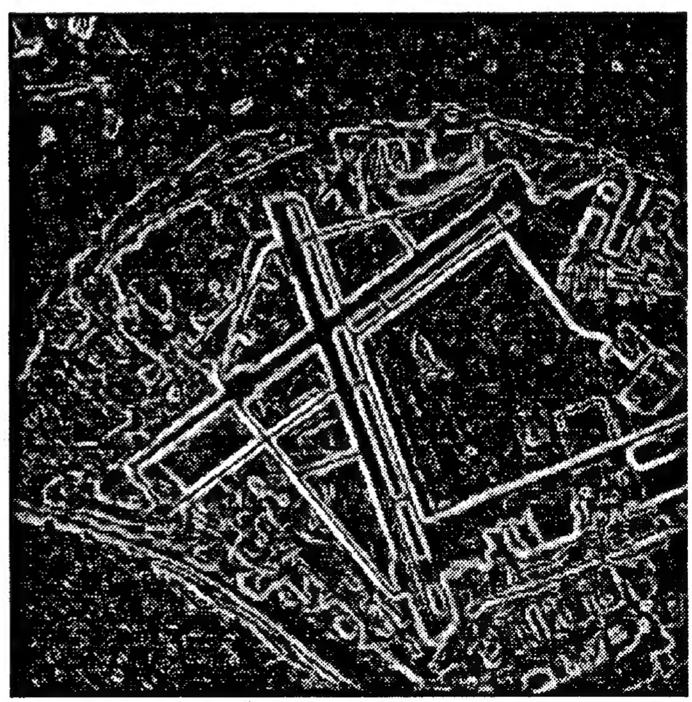
a) TV restoration with segmentation



b) Wiener filter restoration

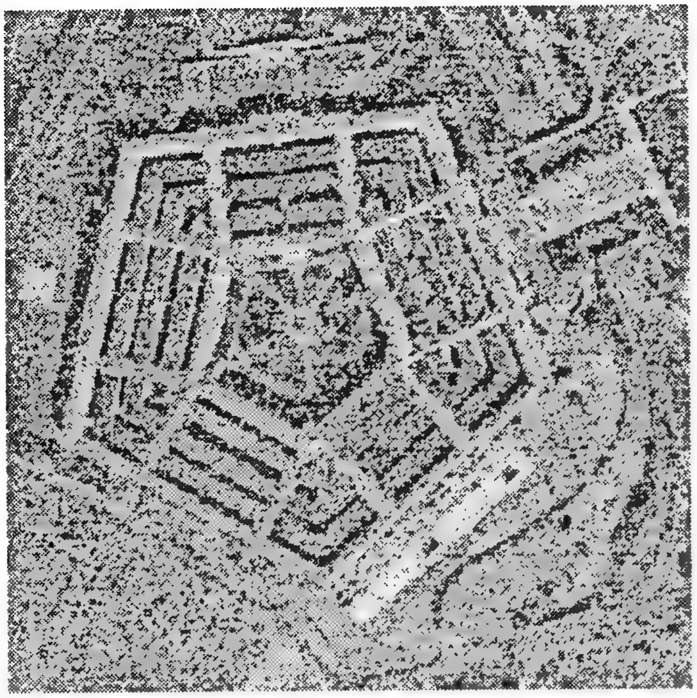


c) Edge detector of TV restoration



d) Edge detector of Wiener restoration

Figure 6



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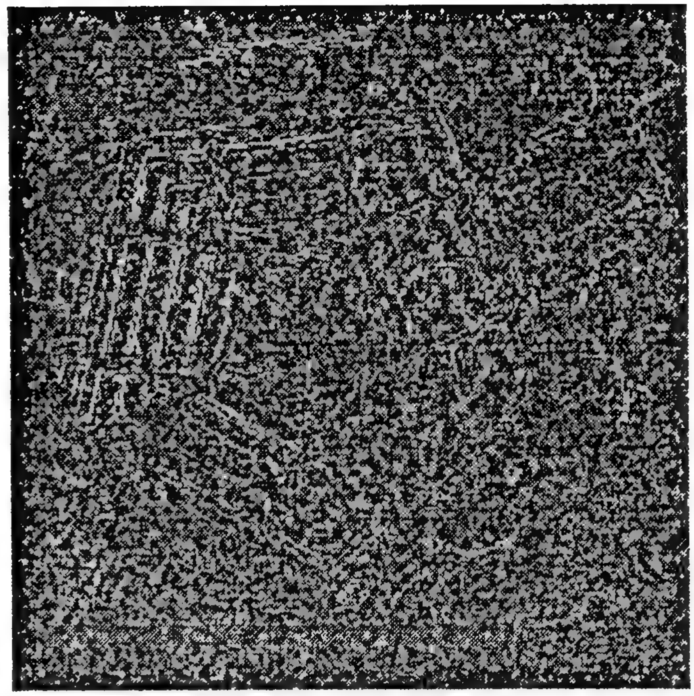
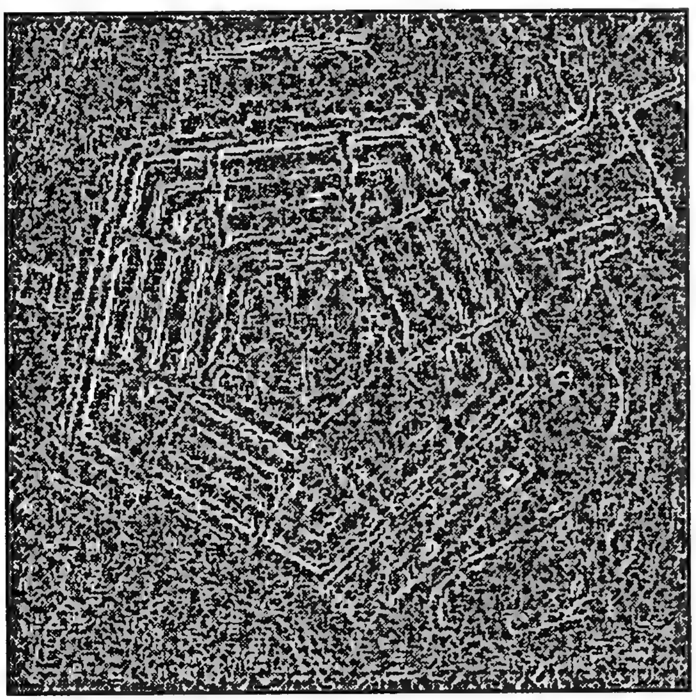
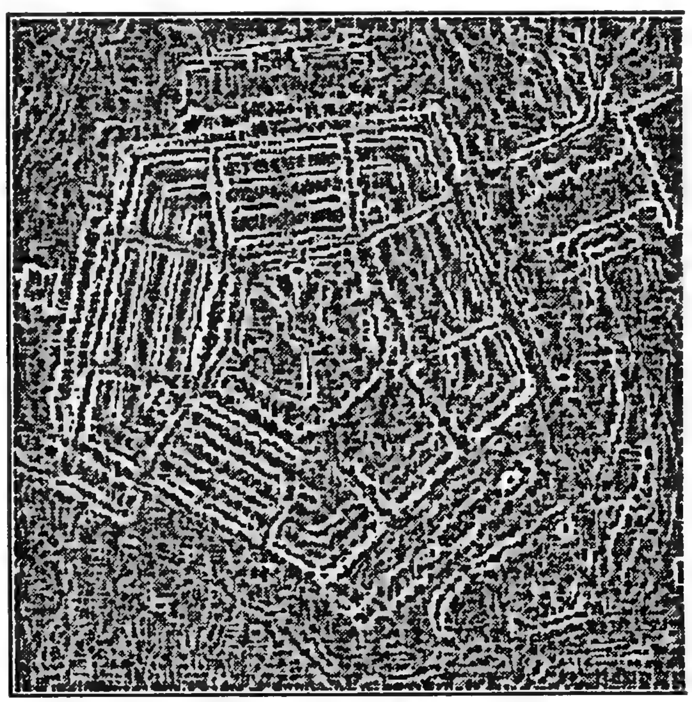


b) Roberts edge detector

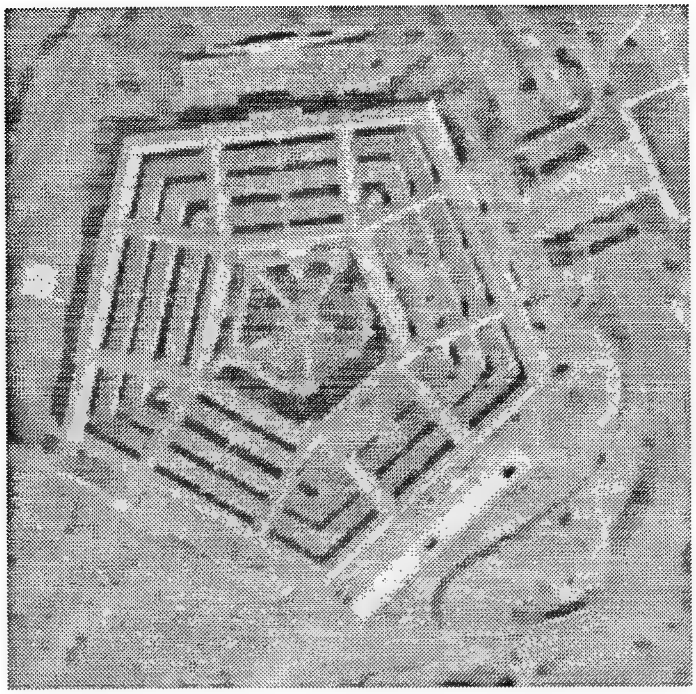


c) Rudin edge detector with 1x2 mask



d) Rudin edge detector with 2x3 mask

Figure 7



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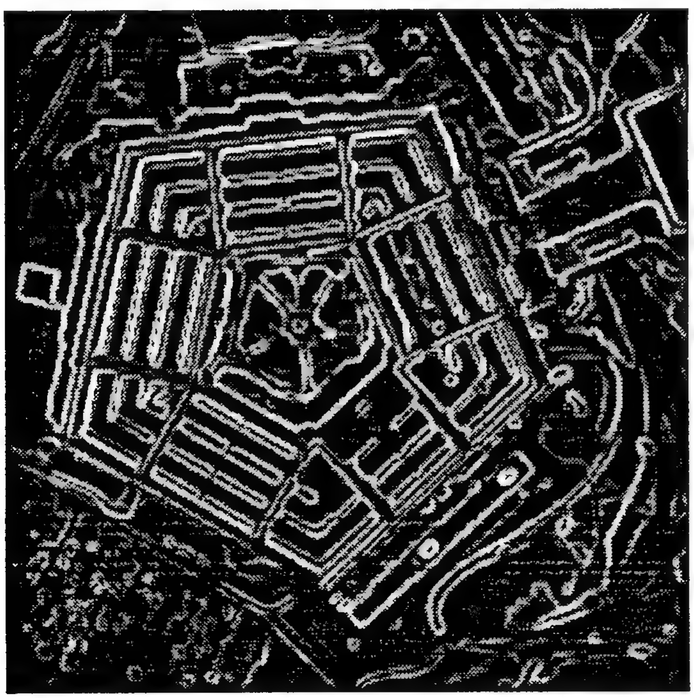
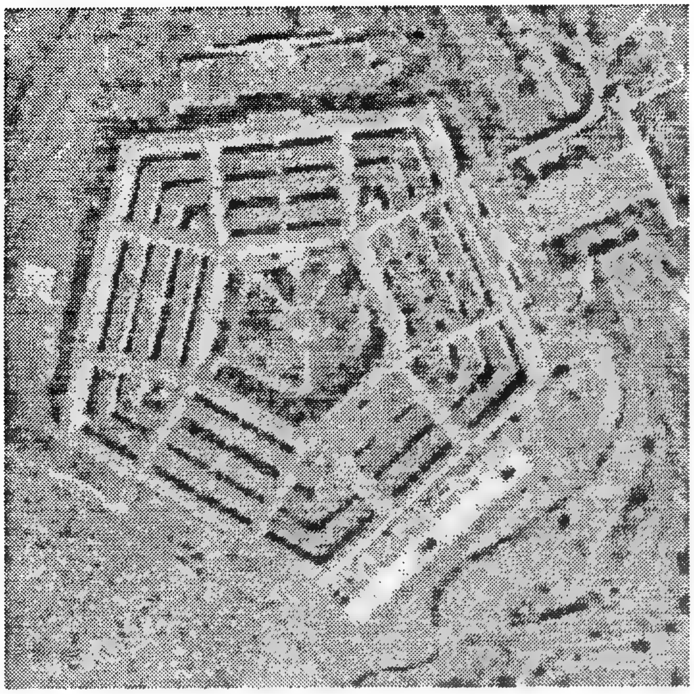


b) Edge detector of TV restoration

Figure 8



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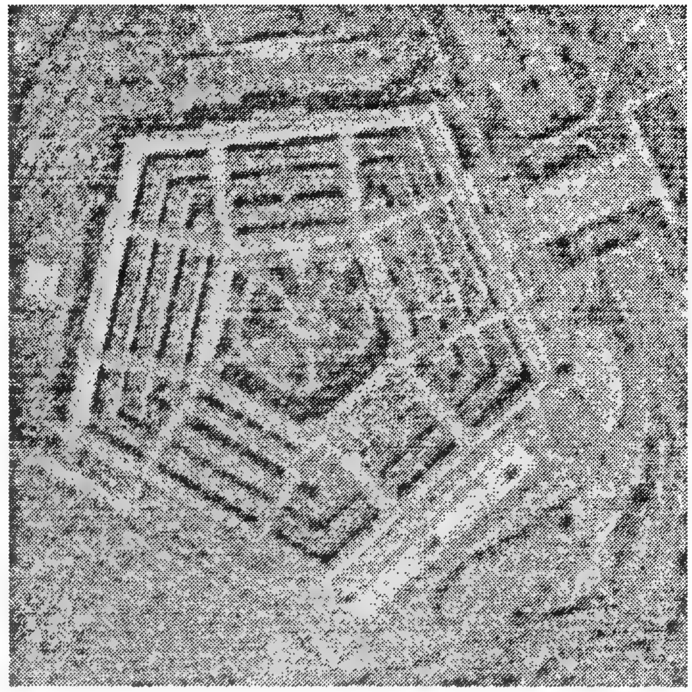

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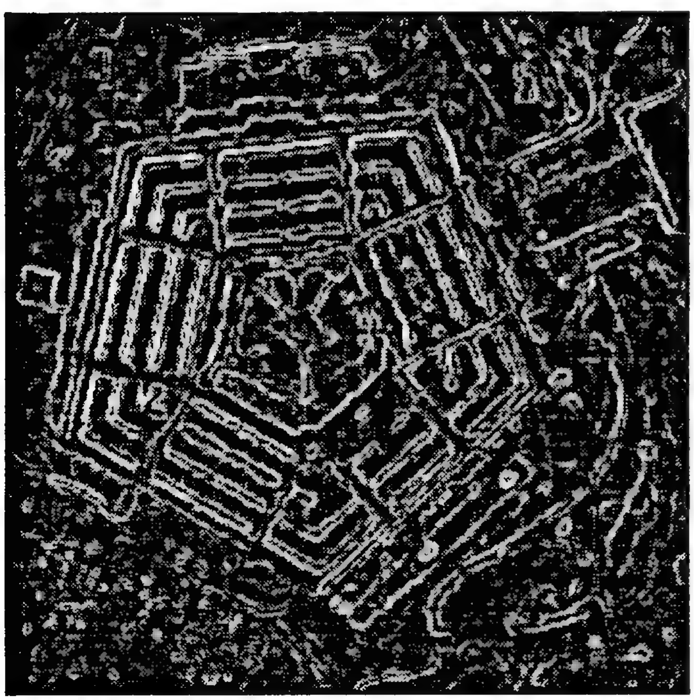
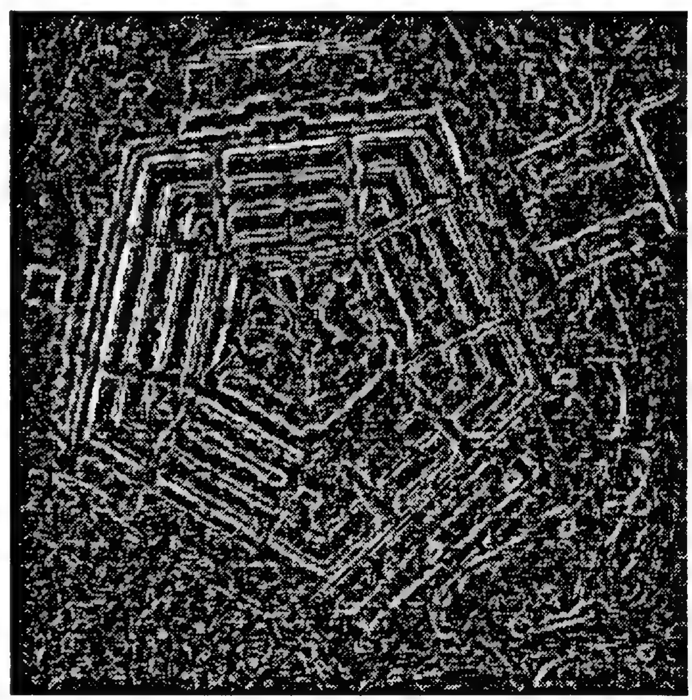
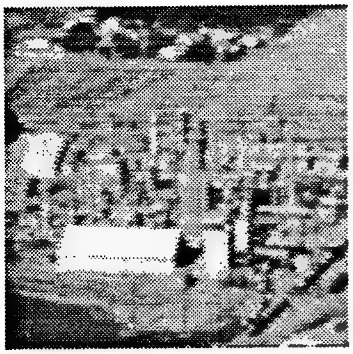


c) Edge detector of TV restoration



d) Edge detector of Wiener restoration

Figure 9



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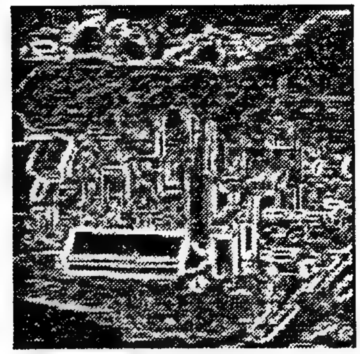
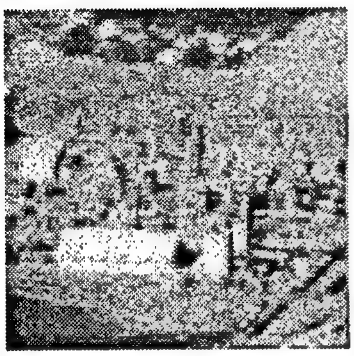
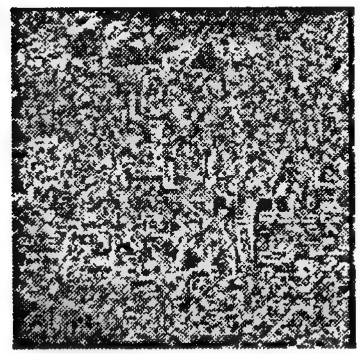


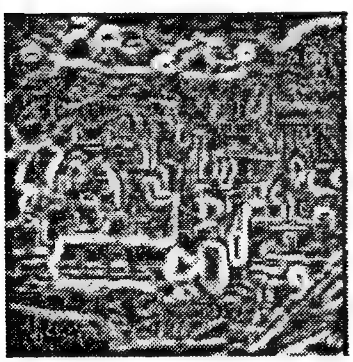
b) Edge map of "a"



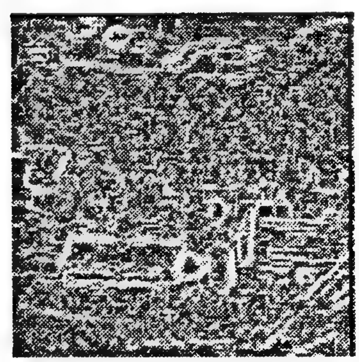
c) Multiplicative noise with st.dev. 0.3



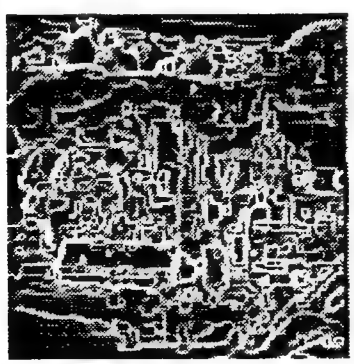
d) Edge map of "c"



e) Edge map of constrained least-square restoration

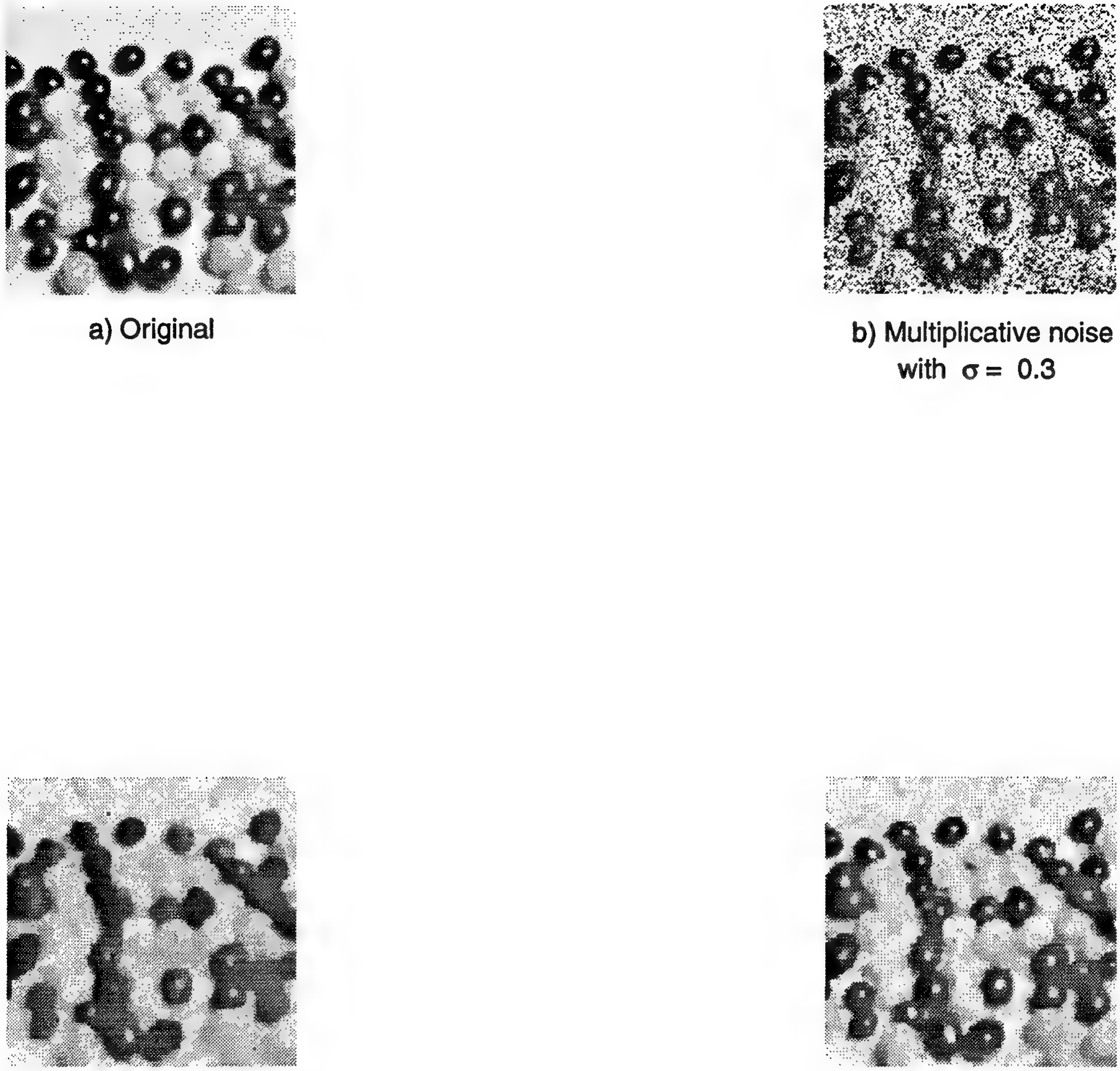


f) Edge map of Wiener filter restoration



g) Edge map of Cognitech's T.V. restoration with segmentation

Figure 10



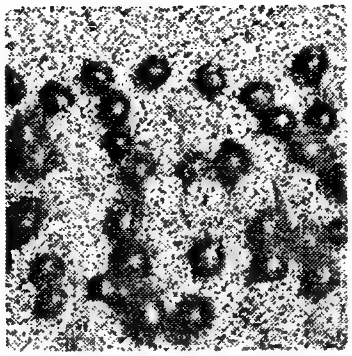
a) Original

b) Multiplicative noise with $\sigma = 0.3$

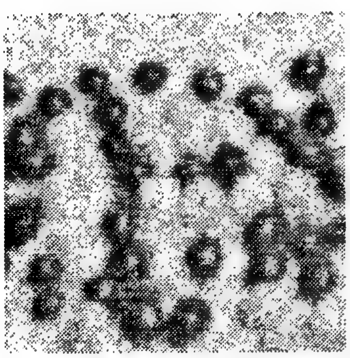
c) Restoration of "b" using Cognitech's TV filters

d) Restoration of "b" using segmentation of original image

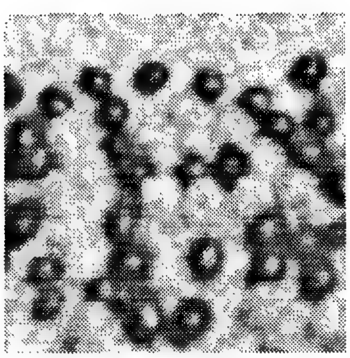
Figure 11



a) Multiplicative noise
with $\sigma = 0.3$

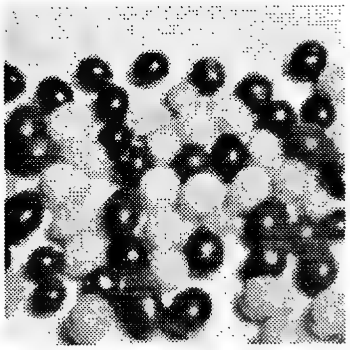


b) Wiener filter
restoration of
"a"



c) Constrained
least - square
restoration of
"a"

Figure 12



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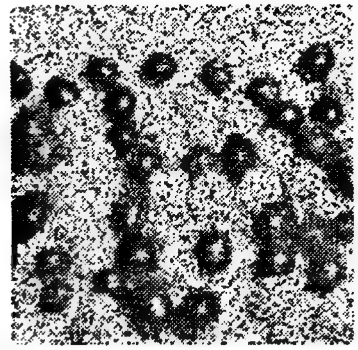
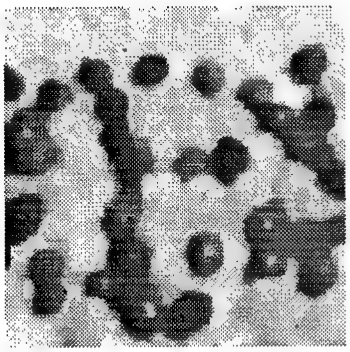
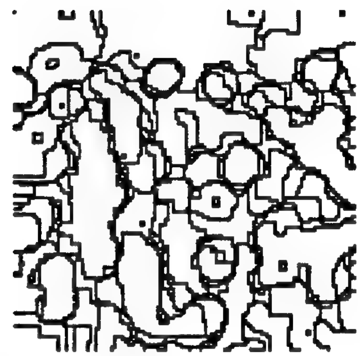


b) Multiplicative noise with $\sigma = 0.3$

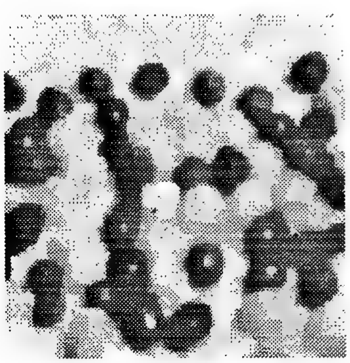


c) Restoration of "b" using Cognitech's TV filters



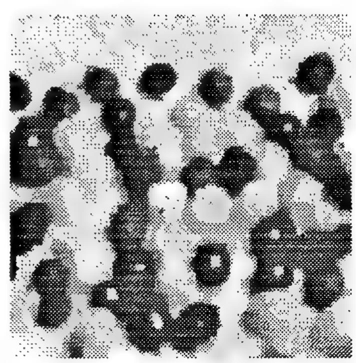
d)Segmentation of "c"

Restoration using iterative segmentation / TV denoising



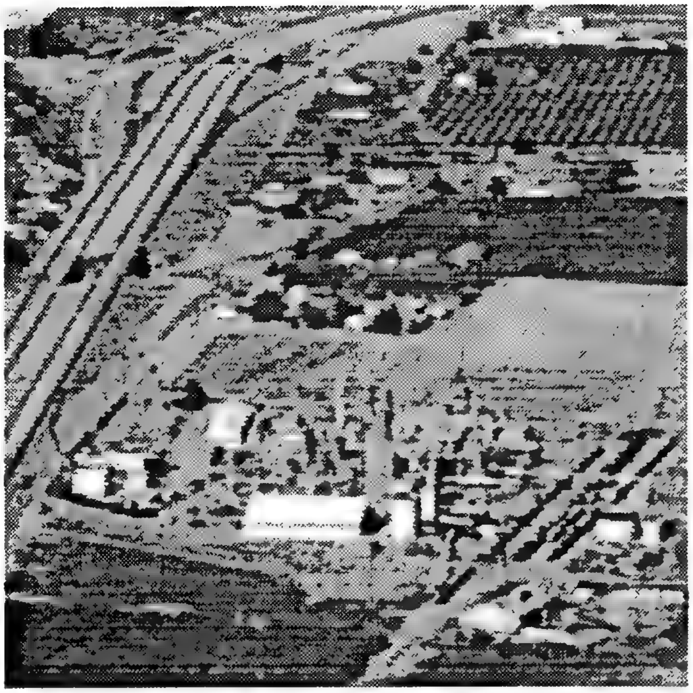
(t1)

(t2)

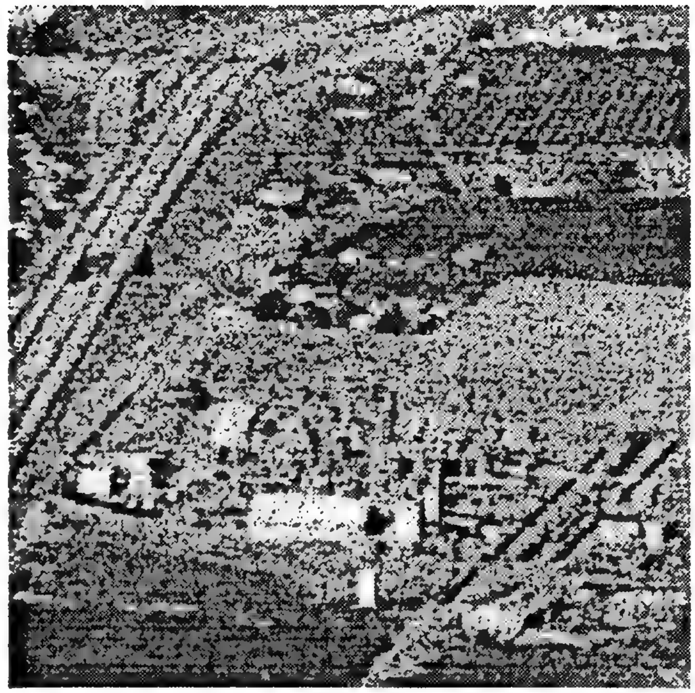


(t3)

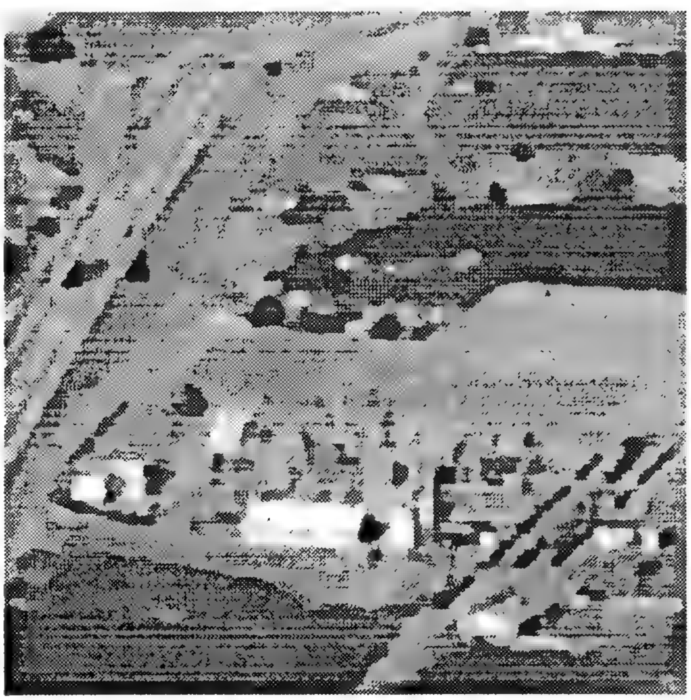
Figure 13



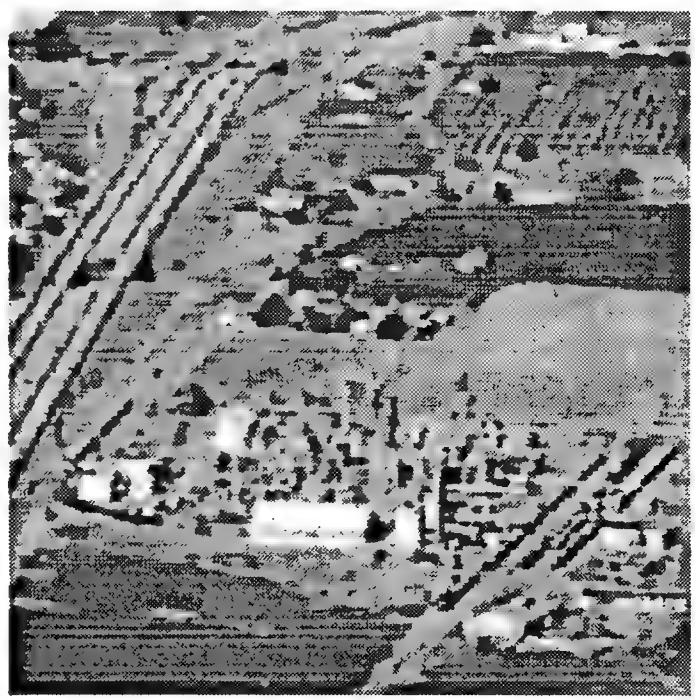
a) Original



b) Multiplicative noise with
$\sigma = 0.25$

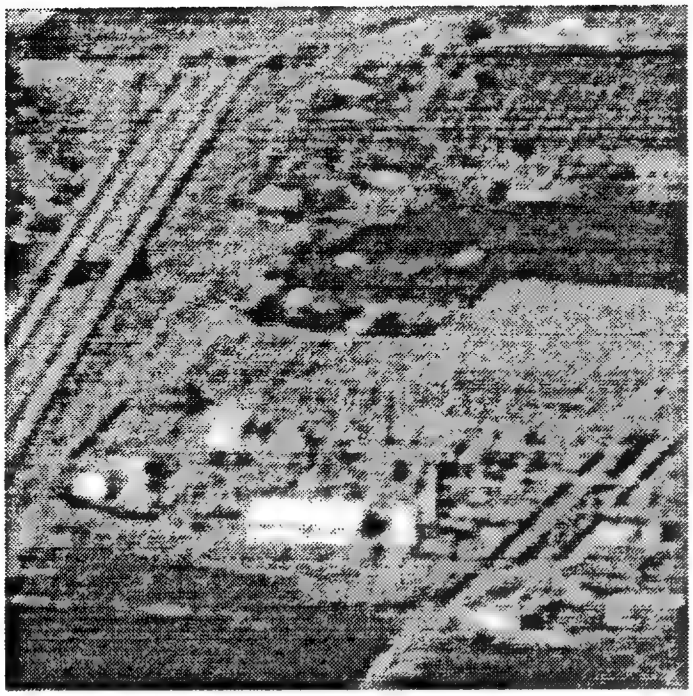


c) Restoration of "b"
using Cognitech's
nolinear filtering



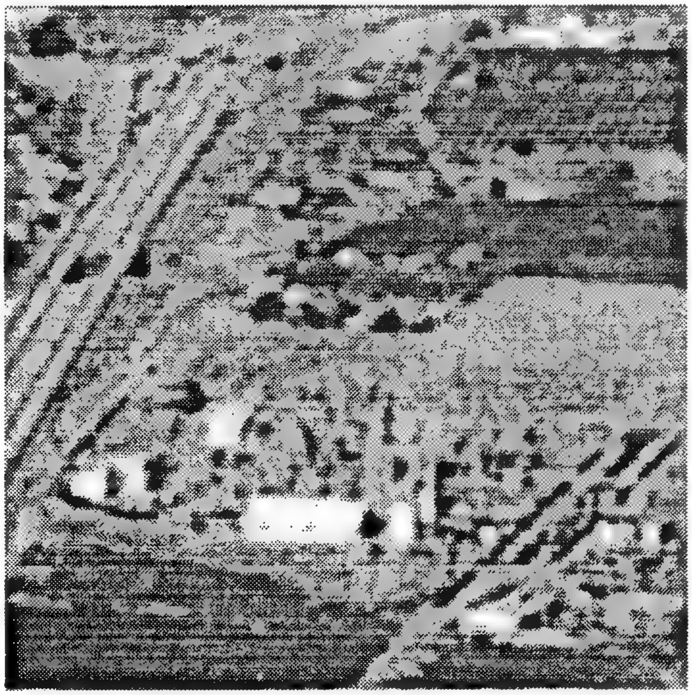
d) Restoration of "b" using ideal
segmentation of original
image

Figure 14

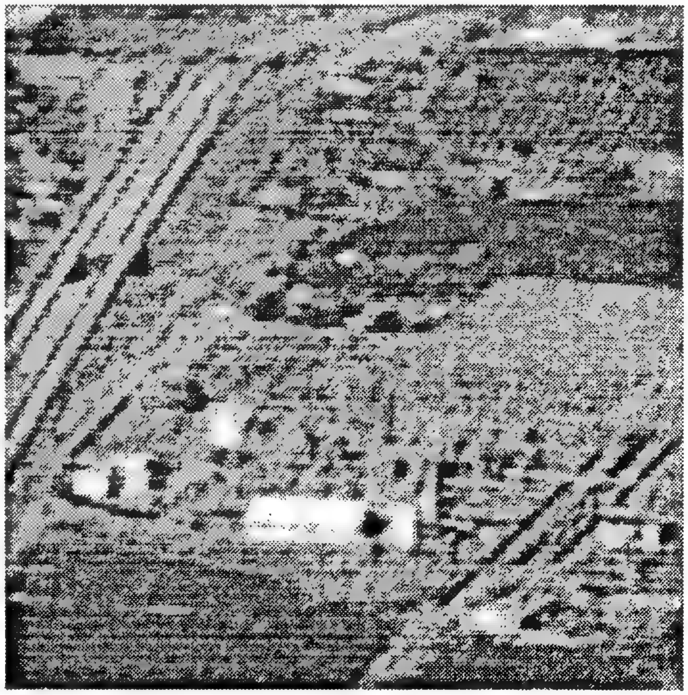


e) Wiener filter restoration of "b"

f) Segmentation of "e"

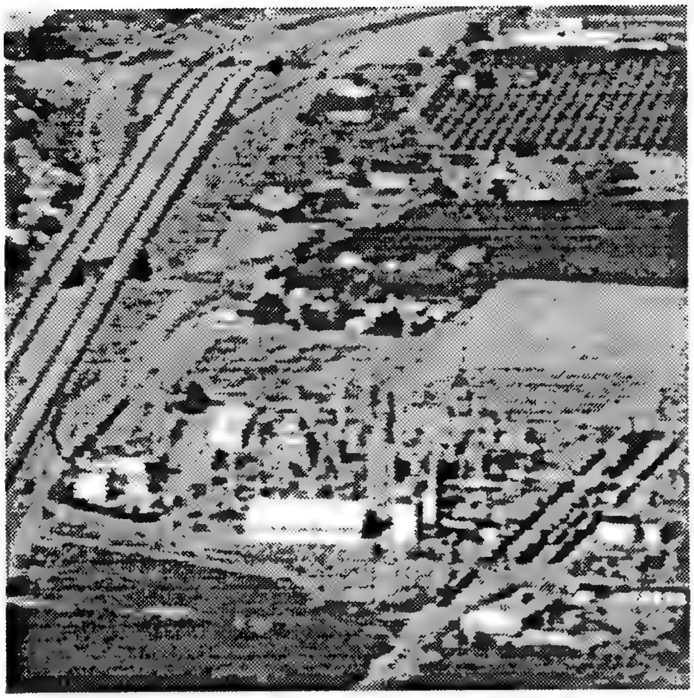


g) Constrained least - square restoration of "b"

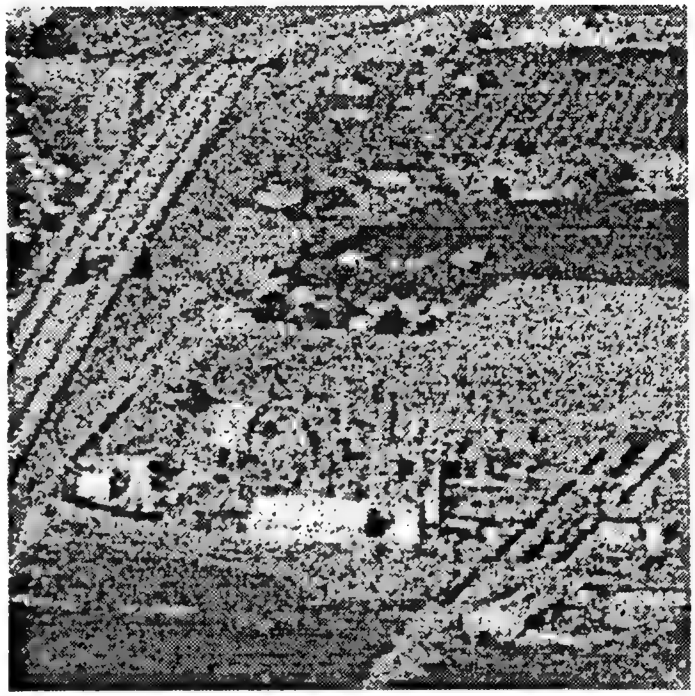


h) Geometrical mean filter restoration of "b"

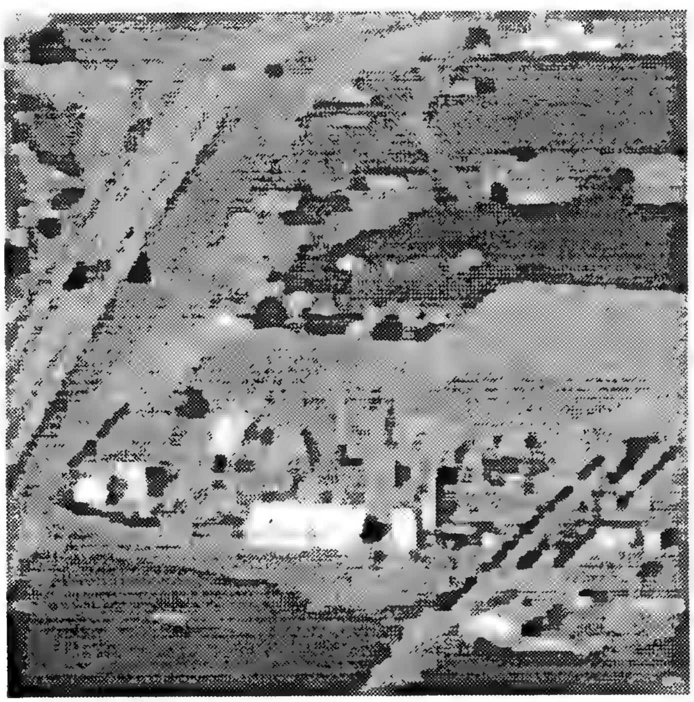
Figure 14
(Continued)



a) Original



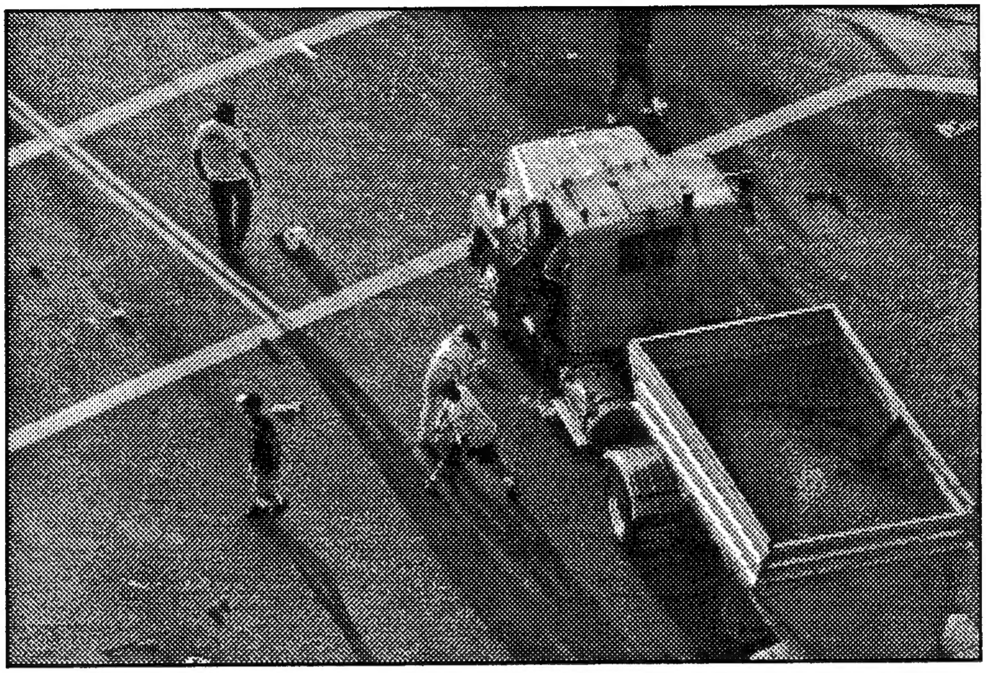
b) Multiplicative noise with
$\sigma = 0.25$



c) Restoration of "b"
using Cognitech's
T.V. filter

d) Restoration of "b"
using Cognitech's T.V.
filter with segmentation

Figure 15

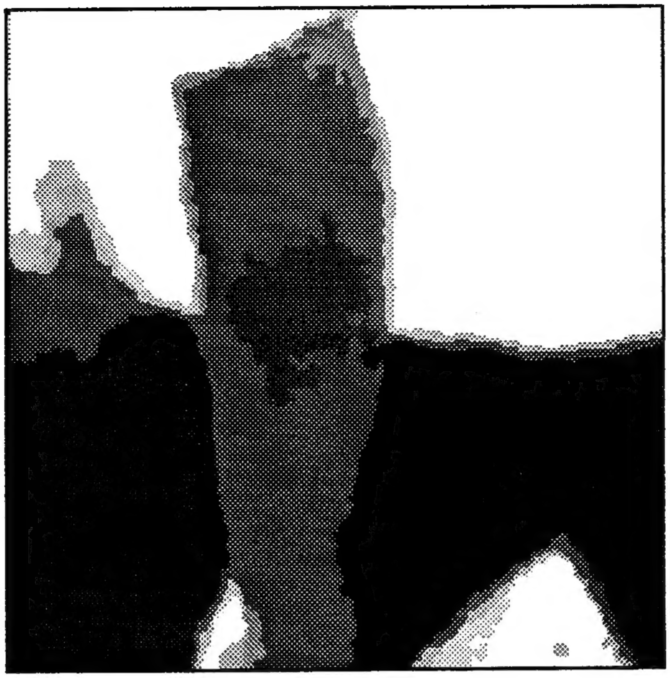


a) Original Image

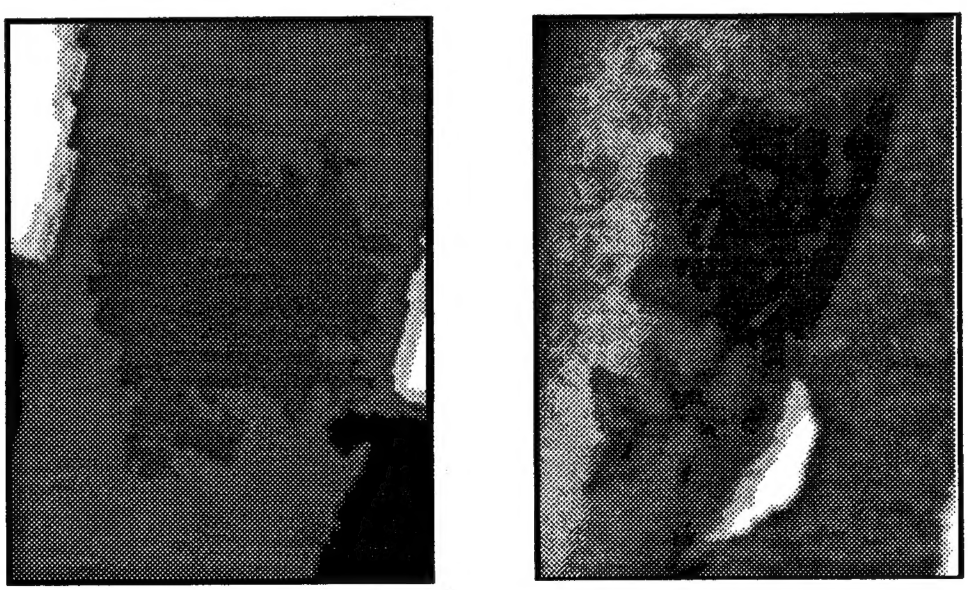
b) Expansion of Arm, using Cognitech's Expansion Algorithm

c) Segmentation of Arm, showing region of suspected tatoo

Figure 16



d) Reconstruction of segmented Arm



e) Comparison between reconstructed image and actual tatoo

Figure 16
(Continued)

a) Original Digitized Field (even lines)

b) Original Digitized Field (odd lines)

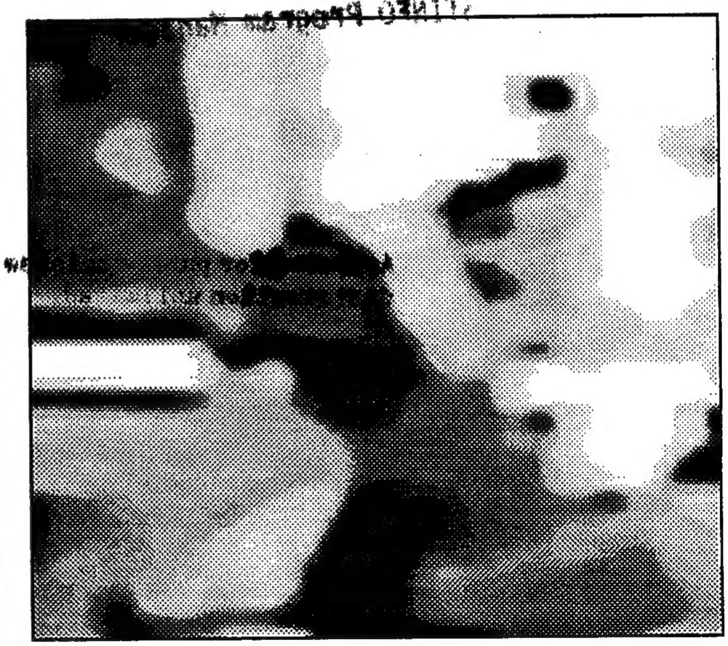
c) Expanded Frame, using simple interlacing of the above two fields

d) Expanded Frame, using Cognitech's Frame Matching Algorithm

Figure 17

e) Expanded view of interlaced frame, showing artifacts.

f) Expanded view of matched frame, showing increased detail



g) Expanded view of matched frame after restoration with Cognitech's TV filters.

Figure 17
(Continued)